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Observation on laser induced lens effect in sound generation under water using high power ultrashort pulse laser

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ABSTRACT

The ultrashort pulse of Nd:YAG laser system is used to generate the sound in water. The picosecond laser beams are focused at two points in experiments. This effect implies that the time response is inherent due to the changes of index of refraction of water induced by laser beam intensity.

Keywords: Ultrashort pulse, mode-locked laser, train pulse, single pulse, laser induced lens, index of refraction of water, shock wave, focusing spots, sound wave, bifocus effect

1. INTRODUCTION

Since Bell[1] discovered the photoacoustic effect in 1880, the generation of sound in water by photoacoustic effect has been proposed again hundred years later[2]. Generation photoacoustic effect using laser beam with very high intensity is an attractive method. According to the energy emitted by the laser, three mechanisms fall under the generation of sound: (1) thermoacoustic, (2) evaporation and (3) optical breakdown. In this paper, the ultrashort pulse laser has been used to generate the sound under water. An effect of laser induced lens has been observed obviously. There are two focusing spots in water. One of them is the convex lens used for focusing laser beam to produce focusing spot. Other is laser energy induced lens, which produces induced focus spot. The time process occurs when the index of refraction of water is changed, the variety of index of refraction is induced by laser beam. This phenomenon can be used to estimate the response time of the changes of index of refraction of water.

2. EXPERIMENT RESEARCH

The ultrashort pulse laser is a Nd:YAG mode-locked laser[3], which consists of oscillator and two stages amplifiers. Passive mode-locking dye cell for short pulse duration and active acousto-optics modulation for stabilization are combined in the oscillator. It is possible to generate extremely reproducible mode-locked pulses with Gaussian temporal and spatial profile. The transverse mode structure is TEM_{oo}. Usually the output of ultrashort pulse is a train of 10 pulses as shown in Figure 1. A single pulse selector is used to select one pulse from the train for amplification. The train pulse and single pulse laser beam are used for research the photoacoustic effect respectively. The duration of single pulse is 40 picosecond. The envelope of train pulse is 100 nanosecond contains 10 pulses with pulse duration 40 picosecond. The separation between two pulses is 10 nanosecond. The power intensity of laser pulse is more than 10^{10} W/cm^2.

The set-up of the experiment is shown in Figure 2. The laser beam is splitting into two beams by an optical splitter. One of them is focused by a convex lens. The focusing spot is located under the water surface at 2cm. Other beam is going to photodiode for monitor the energy of laser beam. The sound induced by laser beam in water is detected by a Hydrophone (piezoelectric transducer). The frequency response is straight in the frequency band 1-10MHz and the sensitivity is about 0.5 μ v/Pa.

When the laser beam is focused by the convex lens at 2cm under water surface, the hydrophone is located at the 4cm under the water surface and 1.5cm apart the laser beam. The waveform of the sound pulses have been detected by hydrophone. The results are shown in Figures 3-5 with pulse duration 40 picosecond. In figures 3 and 4 the waveform is induced by train pulse of laser. The waveform in figure 3 is the case of lower intensity 6×10^{10} W/cm^2, the shock wave does not be excited on the water surface. In figure 4 the intensity of laser beam is stronger as 25×10^{10} W/cm^2, in this case the shock wave is excited on water surface. The waveform induced by a single pulse is shown in Figure 5. For this case the laser beam intensity is 6.4×10^{10} W/cm^2, similar to that for the case of figure 3, but the shocks excited on the water surface, likes that in figure 4. For the case of figure 3, the laser beam intensity for every pulse in train pulses is about ten times lower than the single pulse of laser beam in the case of figure 5. While for the case of figure 4, the laser beam intensity of some pulses in train pulse is alike that of single pulse in the case of figure 5. For the case of figure 3, the detected sound waves come from the focus spot 2cm below the water surface. For the case of figure 4 and 5, the detected sound waves come from two different points. One focus spot is located at 2cm below the water surface, and another is 3.3cm below the water surface. It is interesting to note that the sound waves generated from two focusing spots a and b in figures 4 and 5. The sound waves are reflected by water surface as a' and b' in figures 3-5.

3. ANALYSIS OF RESULTS

The phenomenon can be interpreted by nonlinear effect of high power laser beam in water. The induced lens is produced by changes of index of refraction of water. When the intensity of laser beam is low, the beam is focused at the focus spot of optical lens. While the intensity of laser beam is high, the index of refraction of water will be changed by nonlinear effect of high power beam in water. This nonlinear effect produces induced lens in water. Therefore when the intensity of laser beam is high enough to excite the effect of induced lens, the laser beam would not be focused at the focus spot of optical lens, but at the focus spot of induced lens. If the time-width of laser pulse is far longer than the response time, in which the change of index of refraction $\triangle$n of water is taken place, the laser beam would be focused at focus spot by induced lens. If these two times are comparable, but the time of the laser pulse is somewhat longer than the response time, then the head of the laser pulse would be focused at the focus spot of optical lens, because $\triangle$n could not be established. The tail of laser pulse would be focused at the focus spot of induced lens, because the $\triangle$n has been taken place. If the change of index of refraction of water $\triangle$n is negative, the focus spot of induced lens is behind the focus spot of optical lens. If the $\triangle$n is positive, the focus spot of induced lens is before that of optical lens. It means

that the self-induced focus would be caused. The change of index of refraction of water $\triangle n$ is negative, therefore, when the intensity of ultrashort pulse from laser is high, the head of the laser pulse would be focused at the focus spot of optical lens, then the tail of laser pulse would be focused at the focus spot of induced lens. It means that the bifocus effect occurs.

The bifocus effect may be used to estimate the time response for the change of index of refraction of water $\triangle n$. The acoustical energy induced by the head of laser pulse focused at the focus spot of optical lens is proportional to the laser beam energy in the head part of laser pulse; while the acoustical energy induced by the tail part of the laser pulse focused at the focus spot of induced lens is proportional to the beam energy in the tail part of the laser pulse. The ratio of the acoustical energy which comes from the focus spot of optical lens and from the focus of induced lens respectively corresponds to the ratio of the beam energy in the head of laser pulse and in the tail of laser pulse, if the laser pulse is approximately rectangular pulse. So this ratio is equivalent to the ratio of duration occupied by the head and by the tail. Therefore, the time response for the change of index of refraction $\triangle n$ can be estimated roughly using this ratio. The ratio is 0.15 / 0.85 given by our experiments. It implies that the first 15% of laser pulse is focused at the focus spot of optical lens, when the index of refraction of water has not been changed by the laser beam. So the response time for the change of index of refraction of water $\triangle n$ equals to $40ps \times 0.15 = 6ps$. It is interesting to point out that the acoustical method to estimate the response time of $\triangle n$ is simple.

4. Conclusions

The mechanism of the generation of sound in water by ultra-short laser pulse is mainly the optical breakdown. As the optical breakdown is caused in water by high power intensity ultrashort laser pulse, the bifocus effect is produced. For train pulse of laser beam, if the intensity is insufficient to excite the induced lens, the optical breakdown occurs at the focus spot of optical lens. For single pulse or train pulse of laser beam, if the intensity is sufficient to excite the induced lens, the optical breakdown mainly occurs at the focus spot of induced lens. This bifocus effect shows the time process in the change of index of refraction $\triangle n$ in water. So the bifocus effect can be used to estimate the time response of $\triangle n$.

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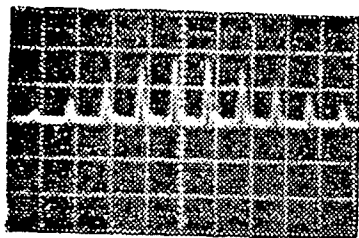
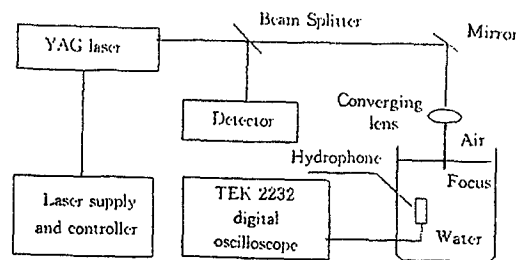Fig. 1. Mode-locked train of pulse
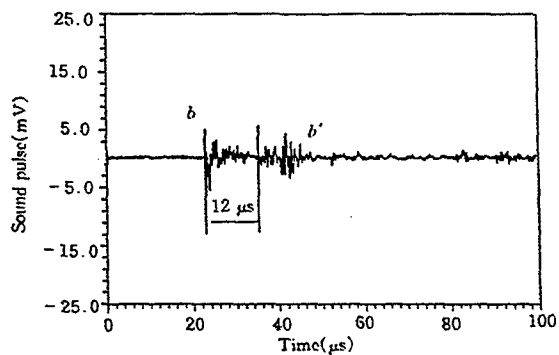Time scale:10ns/cm

Fig. 2. Set-up of the experiment

Fig. 3. Sound generated by train of pulse
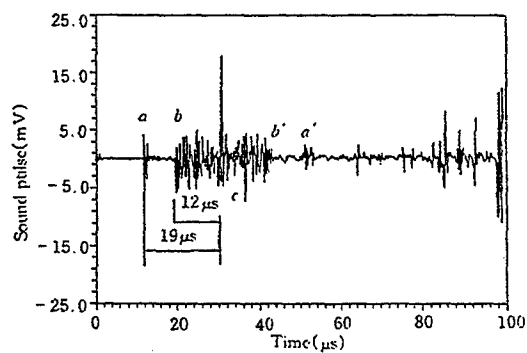with lower intensity

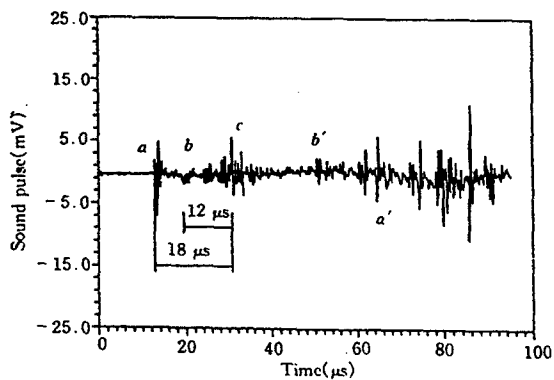Fig. 4. Sound induced by train of pulse
with higher intensity

Fig. 5. Sound induced by a single pulse
with duration 40 ps